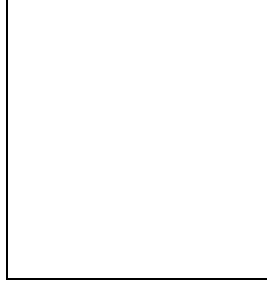# HEAVY FLAVOUR ELECTROWEAK PHYSICS REVIEW

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The four LEP experiments and the SLD detector have measured the Z partial widths in the processes $e^+e^- \to Z \to b\overline{b}$ and $e^+e^- \to Z \to c\overline{c}$ and the corresponding forward-backward asymmetries at centre-of-mass energies close to $m_Z$. The results yield a very precise determination of the effective vector and axial-vector coupling constants and of the underlying electroweak mixing angle $\sin^2\theta_{\text{eff}}^{\text{lept}}$, probing the Standard Model prediction for the electroweak radiative corrections. Of special interest is hereby a difference at the level of three standard deviations in the mixing angle results from lepton production and those obtained from the forward-backward asymmetry in b quark production. The b quark asymmetry measurements, some of which are still in the process of being finalised, are therefore discussed in detail.

## 1   Theoretical Motivation

The forward-backward asymmetries constrain the product of the asymmetry parameters for initial electrons and the final b and c quarks[1],

$$A_{\text{FB}}^{\text{q}, 0} = \frac{3}{4} \mathcal{A}_e \mathcal{A}_{\text{q}} \tag{1}$$

The Standard Model values of the electric charge and the iso-spin for quarks lead to $\mathcal{A}_{\text{q}}$ values for b and c quarks close to 1, hence it is $\mathcal{A}_e$ that $A_{\text{FB}}^{\text{q}, 0}$ is mainly sensitive to. $\mathcal{A}_e$ is a function of the ratio of the effective vector and axial-vector neutral current couplings, $g_{Vl}/g_{Al}$, and thus of the effective electroweak mixing angle $\sin^2\theta_{\text{eff}}^{\text{lept}}$. As a consequence, the results from the forward-backward asymmetry of b and c quarks can be combined with other lepton measurements to determine $\sin^2\theta_{\text{eff}}^{\text{lept}}$ with high precision, and to put constraints on the Higgs boson and top quark mass that enter the effective mixing angle via higher order electroweak corrections. On the other hand, the comparison between the heavy flavour asymmetries and other asymmetry measurements probe the internal consistency of the Standard Model.

In contrast, the measurements of the Z partial decay widths determine the sum of the squares of the coupling constants. In combination with the asymmetry results it is hence possible to disentangle $g_{Aq}$ and $g_{Vq}$.

## 2 Heavy Flavour Electroweak Measurements

The LEP and SLC results for $R_b$ and $R_c$ are final since 2000 [2]. The tools to select b and c events were developed in the framework of these analyses and have been transferred to the asymmetry measurements, where the main experimental task is then to distinguish between the flight directions of the quark and the antiquark. This is achieved by reconstructing the quark charge in one or both of the hemispheres defined by the thrust axis. Two different and largely independent reconstruction methods are applied: one directly yields the clear charge information in case of a weak B decay into a lepton and measures $A_{FB}^b$ and $A_{FB}^c$ simultaneously by means of b-c separation variables. The other approach analyses inclusively all decay types, requiring a flavour-pure data set obtained from b-tagging. Before the asymmetry results are discussed, the lepton and the inclusive method and their sophisticated analysis tools will be briefly presented.

## 3 $A_{FB}^b$ and $A_{FB}^c$ with Leptons

All LEP experiments provide measurements of $A_{FB}^b$ and $A_{FB}^c$ using prompt leptons that are produced with large $p$ and $p_\perp$ in weak decays of b and c hadrons[3,4,5,6]. The $p$, $p_\perp$ of identified electrons and muons are the principal means of distinguishing between $b \to l$ , $c \to l$ , $b \to c \to l$ decays and background. For the purpose of identifying the decay type, new techniques use either neural networks or likelihood ratios to combine the $p$, $p_\perp$ measurement with additional lifetime and kinematic information from the rest of the b- or c-jet. Depending on the experiment, also the jet charge from the opposite hemisphere is included. This has improved the sensitivity to B-$\overline{\text{B}}$ mixing and allowed to measure the b asymmetry also via wrong-sign $b \to c \to l$ decays. $A_{FB}^b$ and $A_{FB}^c$ and possibly the mixing parameter $\chi$ are then extracted from a fit in bins of the decay type identifiers and of $\cos\theta$. The c asymmetry obtained from this method, $A_{FB}^{c,0}$ (leptons) $= 0.0700 \pm 0.0034$, is consistent with the result from exclusively reconstructed D meson decays[7,8,9], $A_{FB}^{c,0}$ (excl. D*) $= 0.0711 \pm 0.0057$.

## 4 Inclusive Jet Charge and New Neural Net Analyses for $A_{FB}^b$

All four LEP experiments exploit also an inclusive approach to measure $A_{FB}^b$ from a large size b-tagged sample with usually very low backgrounds [10,11]. The jet charge that is used in these analyses is correlated to the primary quark, however the charge dilution by fragmentation and subsequent decays limits the sensitivity to $A_{FB}^b$. Therefore ALEPH, DELPHI and OPAL have recently performed [12,13,14] improved measurements that make use of various pieces of information on b-jets combined in a neural network whose output is correlated to the primary b quark charge. The information comprises not only the jet charge but also the secondary vertex charge that provides a reliable charge reconstruction in case of long-lived B$^\pm$ mesons. Additional precision is gained by including identified particles, be it in the $b \to c \to s \to K^-$ decay chain, or via more inclusive $B_x$ charge tags that weight the charge at the secondary and primary vertex depending on the B hadron hypothesis. The output of such a network is displayed for the OPAL and DELPHI data of 1994 in Fig. 1, showing a very pure $\overline{b}$ (b) identification at large positive (negative) values. Based on its charge output $Q$, $A_{FB}^b$ is extracted from the average charge flow

$$\langle Q_F - Q_B \rangle = \sum_f \mathcal{P}_f(\theta)\delta_f(\theta) \cdot A_{FB}^f \cdot \frac{8}{3} \frac{\cos\theta}{(1 + \cos^2\theta)} \quad , \tag{2}$$
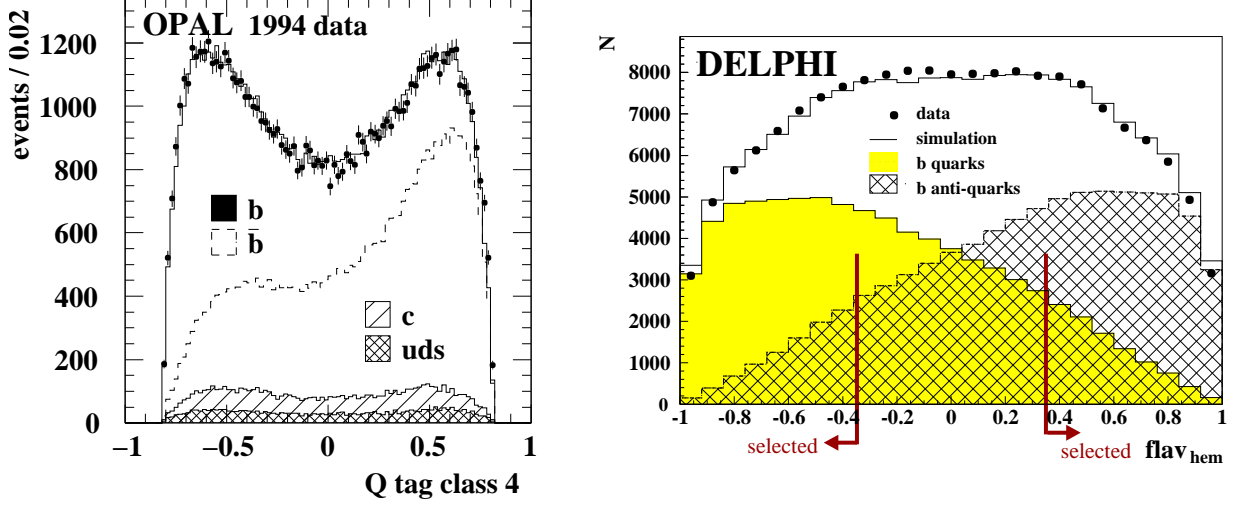
Figure 1: The output distribution of the OPAL and DELPHI charge tagging neural networks for the data of 1994 in comparison with simulation.

using a very comprehensive hemisphere tag (ALEPH) or separate classes of differently composed tags (OPAL) to build $Q_F - Q_B$. DELPHI uses the counting method

$$\frac{N_F - N_B}{N_F + N_B} = \sum_f \mathcal{P}_f(\theta)(2w_f(\theta) - 1) \cdot A_{FB}^f \cdot \frac{8}{3} \frac{\cos\theta}{(1 + \cos^2\theta)} \qquad (3)$$

with a cut-based selection of hemispheres. The measurements work on b-enriched samples with b purities of about 90 %, with the flavour fractions $\mathcal{P}_f$ extracted mainly from the data. The calibration of the charge correlation to the initial b quark ($\delta_b$ in Eq. 2 and $(2w_b - 1)$ in Eq. 3) is very important for being independent from B-physics modelling in the simulation. Therefore ALEPH and OPAL calibrate the charge separation $\delta_b$ from the widths of the charge flow and total charge distributions by measuring

$$\bar{\delta}^2 = \sigma^2(Q_F - Q_B) - \sigma^2(Q_F + Q_B) \approx \sum_f \mathcal{P}_f \delta_f^2 \quad . \qquad (4)$$

DELPHI calibrates the probability $w_b$ to identify the quark charge correctly from the numbers of like and unlike sign charged hemisphere pairs. The calibrated $\delta_f$ and $w_b$ are shown in Fig. 2 for the ALEPH and DELPHI analyses. $A_{FB}^b$ is then extracted from a fit to the differential asymmetry. The DELPHI result from the inclusive b asymmetry measurement[13] has been updated, including the LEP 1 off-peak data as well as the LEP 2 Z runs. Key quantities are now calibrated also for the charm background: a double tagging method corrects the charm fraction while reconstructed D* mesons in the opposite hemisphere are used to correct the charm charge sensitivity $(2w_c - 1)$. The new result presented at this conference is $A_{FB}^{b,0} = 0.0978 \pm 0.0030(stat.) \pm 0.0014(syst.)$ and will be included in the LEP combined b asymmetry in summer 2003.

### 4.1 Modelling Dependence and Checks

The remaining corrections that have to be taken from simulation are the individual sensitivity to the hemisphere correlations and the QCD correction. The hemisphere correlations arise mainly from charge conservation in the event and gluon radiation. They amount to $5 - 9\%$ in linear correction factors to $w_b$ and $\delta_b$. Extensive checks have been performed by the experiments, covering the thrust dependence, monitoring the response of the correlation to selected network inputs and comparing to observables on the real data that are sensitive to the hemisphere correlation. Their results are included in the systematic uncertainties.
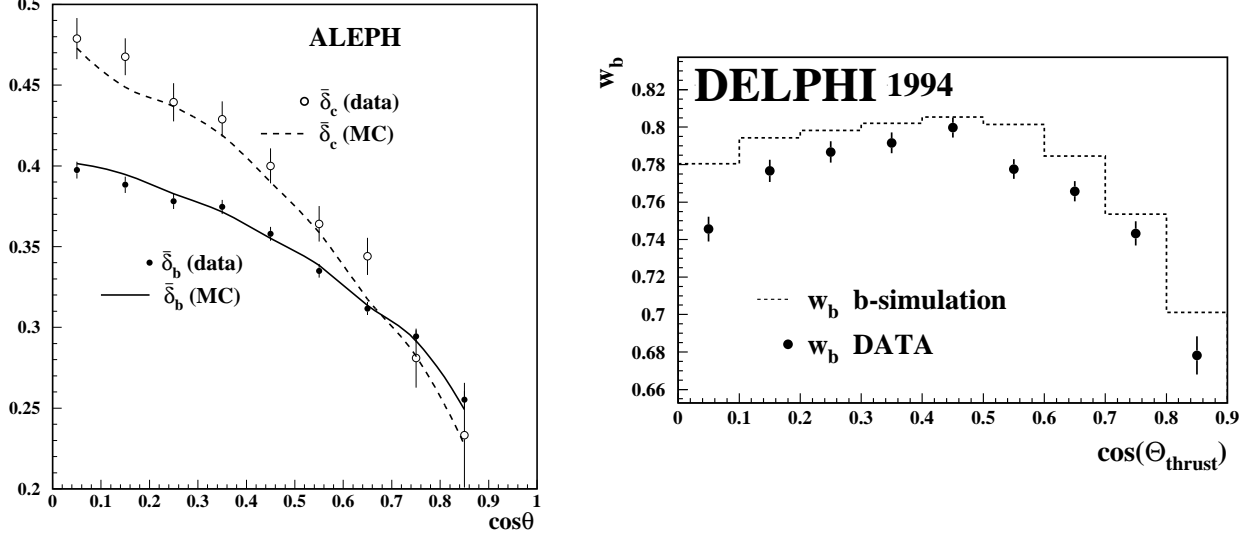
Figure 2: The sensitivities to the b asymmetry in the ALEPH and DELPHI inclusive measurments. The direct measurement on the data is compared to the prediction from the simulation.

The fitted asymmetry values have to be corrected for gluon radiation from the primary quark pair and for approximating their direction of flight by the thrust axis. This QCD correction has been calculated in $\mathcal{O}(\alpha_s^2)$ to be $A_{\text{FB}}^{\text{b, fit}} = (1 - 0.0354 \pm 0.0063) \cdot A_{\text{FB}}^{\text{b}}$, which is more than double the statistical uncertainty of the LEP combined asymmetry result. However the selection of high purity b events biases against events with hard gluon radiation, so that only about 1/4 or less of the full effect is observed. Therefore the residual sensitivity to the QCD effects is computed individually in each analysis and the asymmetries are corrected to the quark level. Studies of the thrust cut dependence in the improved jet-charge analyses revealed that the correction for hemisphere charge correlations in the determination of the charge tagging power directly from the data also absorbs part of the QCD correction. Hence both residual effect and hemisphere correlations are taken into account for a safe estimation of the common systematic uncertainty due to the QCD correction.

## 5  Asymmetry Results in the Light of the Standard Model

The results for the b quark pole asymmetry $A_{\text{FB}}^{\text{b, 0}}$ from the four lepton and five inclusive analyses are shown in Fig. 3a. The average statistical correlation between the two types of analyses is $\sim 25\%$. The results represent the status of winter 2003[15] and are very consistent with each other. By taking into account correlations and common systematic errors as well as off-peak measurements (Fig. 3b) in cases where available one obtains the LEP combined result of

$$< A_{\text{FB}}^{\text{b, 0}} > = 0.0995 \pm 0.0017 \quad . \tag{5}$$

The correlated systematic error arises from mainly physics like the QCD correction and light quark fragmentation. Its value of 0.0004 is quoted in Fig. 3a and turns out to be very small. According to Section 1, the measurement of $A_{\text{FB}}^{\text{b, 0}}$ can be used together with direct lepton $A_{\text{FB}}$

| "leptons" – $A_{\text{FB}}^{l, 0}$, $\mathcal{A}_l(P_\tau)$, $A_{\text{LR}}$ | $0.23113 \pm 0.00021$ |
|---|---|
| "hadrons" – $A_{\text{FB}}^{\text{b, 0}}$, $A_{\text{FB}}^{\text{c, 0}}$, $< Q_{\text{FB}} >$ | $0.23217 \pm 0.00029$ |

Table 1: Results for $\sin^2\theta_{\text{eff}}^{\text{lept}}$ from different groups of asymmetry measurements
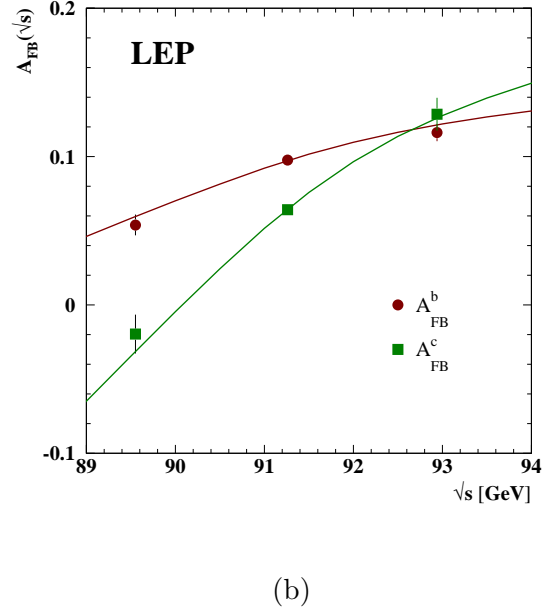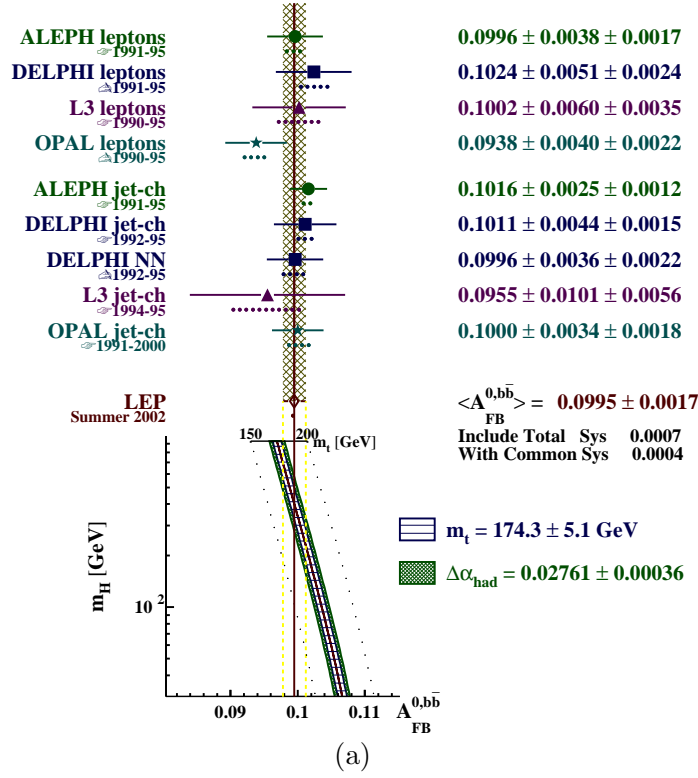
Figure 3: The LEP results for $A_{\mathrm{FB}}^{\mathrm{b},0}$. (a) The average takes into account correlated errors and off-peak measurements. (b) The results for the b and c asymmetry vs. centre-of-mass energy.
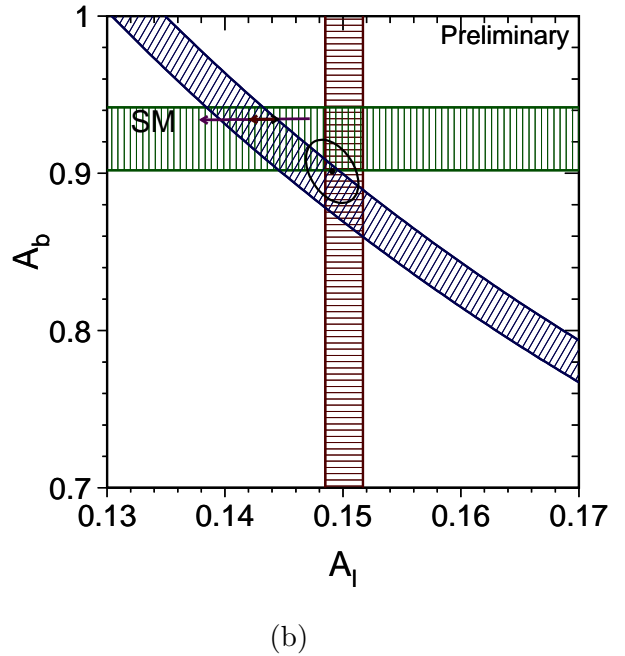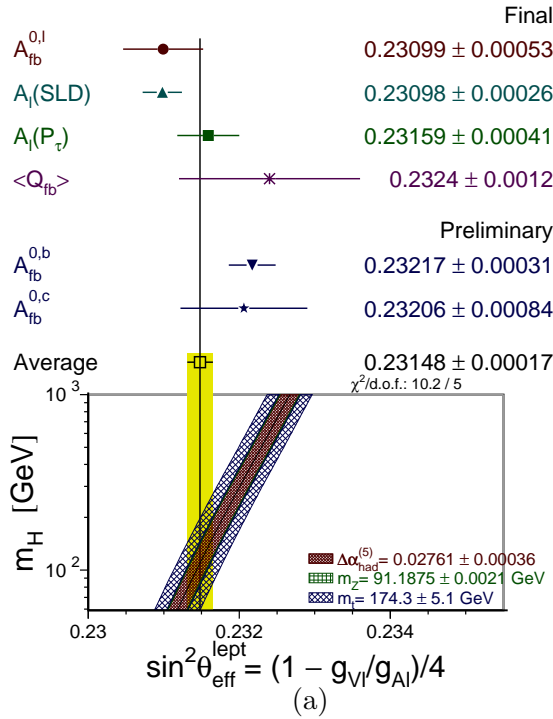


Figure 4: Interpretation of the $A_{\mathrm{FB}}^{\mathrm{b}}$ results in terms of the asymmetry parameters and the leptonic effective electroweak mixing angle. The right plot shows $\pm 1\sigma$ bands in the $(\mathcal{A}_l, \mathcal{A}_{\mathrm{b}})$ plane for $\mathcal{A}_l$ (from the $A_{\mathrm{LR}}$, $A_{\mathrm{FB}}^{l,0}$, and $\tau$ polarisation measurements), for $\mathcal{A}_{\mathrm{b}}$ (from the SLD polarised $A_{\mathrm{FB}}^{\mathrm{b}}$) and for $A_{\mathrm{FB}}^{\mathrm{b},0} = (3/4)\mathcal{A}_l\mathcal{A}_{\mathrm{b}}$ (diagonal band). The small dependence of the Standard Model prediction on $\mathcal{A}_{\mathrm{b}}$ allows a direct comparison in terms of $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$, as shown in the Figure (b) on the left.

measurements and $A_{\mathrm{LR}}$ from SLD[16] to determine $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$. This combination is illustrated in Fig. 4a and shows that the lepton and heavy quark results are not very consistent with each other; a situation that exists since the beginning of asymmetry measurements at LEP and SLC. The averages of the two groups of measurements are listed in Table 1. All six measurements give a combined $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ result of $0.23148 \pm 0.00017$ with a fit probability of 7%.

The electroweak fit itself gives no clear hint of a problem in the Standard Model. For example Fig. 4b shows that LEP and SLC are not inconsistent if both $\mathcal{A}_{\mathrm{b}}$ and $\mathcal{A}_l$ are free parameters, there is a region of common overlap. Although the overlap region agrees poorly with the Standard Model expectation, a single result like $A_{\mathrm{FB}}^{\mathrm{b},0}$ from LEP can still be well compatible. Via higher order corrections to $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$, $A_{\mathrm{FB}}^{\mathrm{b},0}$ is sensitive to $m_{\mathrm{h}}$. Interestingly it is the only quantity that prefers a high Higgs boson mass, thus making the electroweak fit more compatible with the direct exclusion limit on $m_{\mathrm{h}}$[15,17].

## 6   Concluding Remarks

Heavy flavour foward-backward asymmetries have been measured at LEP with various powerful and sophisticated techniques that have set great store on model-independence and self-calibration. The precise results are self-consistent and have a small common systematic error, suggesting that the difference to the combined mixing angle based on leptonic results is rather of statistical nature, if not a hint for new physics. The interpretation of the heavy flavour electroweak results is unchanged since summer 2002, but a conclusive word on asymmetries from LEP is expected in summer 2003 when the final results from DELPHI and OPAL are included in the combination.

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